Sludge accumulation in polishing ponds treating anaerobically digested wastewater

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Abstract
When ponds are used for wastewater treatment, settleable solids will form a steadily growing bottom sludge layer, which reduces their effective volume. Eventually this sludge must be removed to ensure that the pond maintains the required retention time to keep performing properly. The settleable solids may either be present in the influent or they are formed during the treatment as a result of algal flocculation.

An experimental investigation was carried out to evaluate bottom sludge accumulation in a polishing pond used for treatment of UASB effluent. The mass and composition of the bottom sludge formed in a polishing pond was evaluated after the pilot scale pond had been in operation for 1 year and about 60 m³ of digested wastewater had been treated per m³ of pond. The bottom sludge mass represented a solids accumulation of 70 g per m³ of digested wastewater. About half of these solids were the result of settling of influent solids in the first part of the pond, while the other half was attributable to settling of algae, formed in the pond. It is concluded that the bottom sludge growth in a polishing pond is so low, that desludging during the useful life span of the pond will most likely not be necessary. This leads to the important conclusion that excess sludge discharge from UASB reactors (a major factor in operational costs) may be omitted, if a polishing pond is used for post-treatment. The bottom sludge had a high volatile solids concentration (58%) and the macronutrient fractions were also high (3.9% N and 1.1% P of the TSS mass). The bottom sludge was stable and could be dried directly without problems. The hygienic quality of the bottom sludge was very poor: about half the influent helminth eggs during one year of operation were found in the bottom sludge and the faecal coliform concentration was very high.

Keywords
Polishing ponds; sludge; accumulation rate; hygienic quality; stability

Introduction
Settling of particulate material in raw wastewater is one of the main processes to remove organic material from the liquid phase in conventional waste stabilisation pond (WSP) systems. In the typical configuration of conventional WSPs (anaerobic + facultative + maturation ponds), the anaerobic pond receives the influent, in which the settleable material is present as a suspension. During the retention in the anaerobic pond (which is usually in the range of 1 to 5 days; Mara and Pearson, 1998) the settleable solids will be removed to become part of a sludge formed at the bottom of the pond. Decanted wastewater with a much lower suspended solids concentration and a correspondingly smaller organic material concentration is discharged into the subsequent facultative pond. The removal efficiency of the organic material and suspended solids is in the range of 50% to 70% (Vincent et al., 1963; Yanez, 1993), but a considerable fraction of this material is transformed into biogas by anaerobic digestion. The non-biodegradable residue accumulates at the bottom of the pond, thus reducing gradually its volume, so that the pond performance tends to deteriorate with time. As a result the bottom sludge of anaerobic ponds must be removed every 2 to 5 years depending on the raw wastewater characteristics, the retention time and the average temperature. For this reason often two anaerobic ponds are constructed, one of which can be taken out of operation for desludging. The desludging operation is a major factor in operational costs of conventional WSPs.
Although settling and subsequent anaerobic digestion are important processes in conventional WSPs which contribute to the success of this option for wastewater treatment, the accumulation of the bottom sludge has also negative aspects. The removal of the bottom sludge in itself represents a major factor of operational costs. On the other hand, in the process of the solids decomposition in the anaerobic pond, sulphide is produced and part of this compound is released as hydrogen sulphide in the biogas and thus is a major factor contributing to bad odours that may emanate from conventional waste stabilisation pond systems.

Data for the accumulation of bottom solids vary widely, as they depend on the composition of the influent and the operational conditions of the pond. The accumulation is often expressed as the volume per inhabitant per annum with a reported range from 0.03 to 0.09 m³ inh.⁻¹ annum⁻¹ (Arceivula, 1985). Also, the concentration of the bottom sludge seems to vary considerably with values, with reported values between 52 (Paing et al., 2000) and 120 g l⁻¹ (Saqqar et al., 1993). From the published data it can be calculated that the mass of accumulated bottom sludge in the case of raw wastewater ranges from 157 to 266 mg l⁻¹ of influent (van Eck et al., 1966; Paing 1999; Yanez, 1993). Unfortunately the bottom sludge production is often given as the rate of increase of the bottom layer thickness, which is only useful if the area of deposition is also given, but this is generally is not the case. In moderate climates the rate of bottom sludge accumulation varies cyclically with steep accumulation during the season with low temperatures and a decrease of the accumulated sludge mass during the summer due to anaerobic digestion (Marais, 1966).

When ponds are used for post-treatment of anaerobically digested wastewater, the nature and the concentration of the settleable matter is very different from those in raw wastewater. If no excess sludge is removed from the anaerobic treatment unit (for example, a UASB reactor), the suspended solids of the raw wastewater are efficiently removed: 70% to 80% in UASB reactors with retention times in the range of 4 to 6 h (van Haandel and Lettinga, 1993). Most of the settleable solids in the anaerobic effluent will be anaerobic sludge particles. The production of these solids in the anaerobic treatment unit is in the range of 15% to 25% of the organic material concentration (van Haandel and Lettinga, 1993), i.e. of the order of 100 to 150 mg STS l⁻¹. Under steady state conditions, if no excess sludge is discharged, the (settleable) sludge concentration in the effluent will be equal to the sludge production in the UASB reactor. If excess sludge is discharged regularly from the UASB reactor, the settleable solids concentration in the anaerobic effluent is much lower, usually well below 100 mg l⁻¹ (Cavalcanti et al., 1999). This is very much lower than the suspended solids concentration in raw wastewater, typically in the range of 400 to 600 mg l⁻¹. The accumulated sludge is always smaller than the mass of suspended solids in the influent, not only because not all suspended solids do actually settle out, but also because a fraction of the influent solids is biodegradable and will be converted into biogas by anaerobic digestion taking place in the bottom sludge.

On the other hand, the configuration of well designed polishing ponds for anaerobically digested wastewater is very different from that of a conventional waste stabilisation pond system. Organic material removal in polishing ponds is a secondary consideration; normally the main objective is pathogen removal. This can best be achieved in a single polishing pond, especially if this pond is subdivided in sections or lanes by appropriately placed baffles so that mixing is minimised (Cavalcanti et al., 2001). The settleable solids of the anaerobically digested sludge will tend to be deposited in the first lane of the polishing pond.

**Experimental investigation and results**

The bottom sludge accumulation was evaluated in a pilot scale polishing pond treating UASB effluent under tropical climatic conditions. The UASB reactor treated raw municipal
wastewater with an average temperature of 25°C. The UASB reactor had a very short retention time (only 3 hours), but due to an efficient phase separator design (Cavalcanti et al., 2001), it exhibited a good operational stability and a high treatment efficiency. COD and BOD removal efficiencies were 70–80% and 80–85% respectively. The BOD and COD concentrations in the effluent were in the range of 60–80 and 150–200 mg/l respectively, but an appreciable part of these could be attributed to sludge particles. Algal populations were established in every lane. The UASB reactor was operated without discharging excess sludge, so that the sludge mass in its effluent was equal to the sludge production. The average suspended solids concentration was 122 mg STS.l⁻¹ with an organic material fraction of 65% and the settleable solids amounted to 1.2 ml.l⁻¹. Stability tests of the UASB effluent solids showed that a fraction of 15 to 25% of its solids was biodegradable in an anaerobic environment. The hygienic quality of the digested wastewater was poor with faecal coliforms in the range of 10⁷ to 10⁸ per 100 ml and an average concentration of helminth eggs of 208 units per l. The UASB effluent had a low, variable sulphide concentration (0 to 4 mg/l), but no sulphide was detected (nor perceived) in the polishing pond.

The polishing pond, with a concrete bottom and plastered brick walls, had an effective volume of 32.5 m³ and an area of 50 m². The unit was composed of five parallel lanes, operated in series, each 10 m long, 1 m wide and 0.6 to 0.7 m deep. Figure 1 shows a schematic layout of the polishing pond, as well as the interconnections between the lanes. The pond was operated over a period of 1 year with total retention times of 5 to 7.5 d, so that over a year approximately 2000 m³ of digested wastewater was polished in the pond. Thus the mass of suspended solids over the operational period of 1 year was estimated at 2000 * 0.122 = 244 kg STS.

In order to evaluate the mass and volume of the bottom sludge after one year of operation the following procedure was applied: the influent flow was stopped and the supernatant of the effluent was siphoned off from each lane, taking care that no bottom sludge was lost in the process. The remaining thick fluid exhibited a clear density stratification. To obtain representative samples, the bottom sludge was thoroughly mixed and samples were taken for the characterisation of physical, chemical and biological properties of the solid fraction of the bottom sludge in each lane. Physically, the bottom sludge was similar to biological sludge: it had no macroscopic particles with firm mechanical strength like those encountered in bottom sludge of anaerobic ponds. Presumably these particles were retained in the preceding UASB reactor.

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**Figure 1** Layout of the pilot polishing pond and structure of the interconnections between lanes
The data in Table 1 summarise the values of the bottom solids mass, composition and properties in each of the five lanes, as well as in the total sludge mass. The solids fraction of total solids in the fluid after siphoning of the supernatant was actually higher than the figure given in Table 1 because, in order to avoid loss of solids, some water had to be left. It is estimated that the real humidity of the bottom sludge was about 90% instead of the value of about 95% in Table 1, i.e. in the pond the sludge concentration was estimated at about 100 g/l. Standard Methods (1997) procedures were followed where these were available to carry out the tests for bottom sludge characterisations. Chlorophyll a was determined by the extraction method described by Pearson et al. (1987). The number of helminth eggs was estimated by using the Yanko recovery method described in USEPA (1992). Sludge stability was calculated after incubating sludge samples at 30ºC during one month after dilution with pond effluent. During this incubation the accumulated methane production was observed. Methane production was more intense during the first few days of incubation: in the first week the methane production was always more than half the total production during the test period of one month. The biodegradable sludge fraction was calculated both from the measured methane production (van Haandel and Lettinga, 1993) and the reduction of volatile suspended solids. It was observed that hydrolysis and digestion of organic material in the bottom sludge was insignificant: less than 5% of the volatile solids were digested during the incubation period of 1 month at 30ºC (see Table 1).

**Table 1**  Mass and characteristics of sludge accumulated during 1 year at the bottom of a 65 m³ polishing pond with an average HRT of 6 days

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Lane1</th>
<th>Lane2</th>
<th>Lane3</th>
<th>Lane4</th>
<th>Lane5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sludge mass</td>
<td>kg ST</td>
<td>77.3</td>
<td>13.9</td>
<td>21.5</td>
<td>16.4</td>
<td>12.0</td>
<td>141.0</td>
</tr>
<tr>
<td>Volatile sludge mass</td>
<td>kg SV</td>
<td>41.2</td>
<td>7.7</td>
<td>13.8</td>
<td>11.5</td>
<td>8.2</td>
<td>84.5</td>
</tr>
<tr>
<td>Volatile fraction</td>
<td>kgSV/kgST</td>
<td>0.53</td>
<td>0.55</td>
<td>0.64</td>
<td>0.70</td>
<td>0.68</td>
<td>0.58</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>gTKN/gSV</td>
<td>0.054</td>
<td>0.085</td>
<td>0.085</td>
<td>0.081</td>
<td>0.090</td>
<td>0.066</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>gP/gSV</td>
<td>0.013</td>
<td>0.032</td>
<td>0.020</td>
<td>0.022</td>
<td>0.023</td>
<td>0.018</td>
</tr>
<tr>
<td>Chlorophyll a</td>
<td>g/gSV</td>
<td>0.0</td>
<td>0.38</td>
<td>0.44</td>
<td>0.38</td>
<td>0.45</td>
<td>–</td>
</tr>
<tr>
<td>Stability</td>
<td>mgSV/gSV</td>
<td>32</td>
<td>50</td>
<td>45</td>
<td>35.</td>
<td>23</td>
<td>–</td>
</tr>
<tr>
<td>Helminth eggs</td>
<td>no/gST</td>
<td>2071</td>
<td>2151</td>
<td>362</td>
<td>0</td>
<td>0</td>
<td>1.9*10^8</td>
</tr>
<tr>
<td>Coliforms</td>
<td>no/gST</td>
<td>2960</td>
<td>3580</td>
<td>–</td>
<td>6060</td>
<td>3980</td>
<td>–</td>
</tr>
<tr>
<td>Moisture content (%)</td>
<td></td>
<td>95.8</td>
<td>94.6</td>
<td>95.1</td>
<td>95.5</td>
<td>94.2</td>
<td>–</td>
</tr>
</tbody>
</table>

The data in Table 1 summarise the values of the bottom solids mass, composition and properties in each of the five lanes, as well as in the total sludge mass. The solids fraction of total solids in the fluid after siphoning of the supernatant was actually higher than the figure given in Table 1 because, in order to avoid loss of solids, some water had to be left. It is estimated that the real humidity of the bottom sludge was about 90% instead of the value of about 95% in Table 1, i.e. in the pond the sludge concentration was estimated at about 100 g/l. Standard Methods (1997) procedures were followed where these were available to carry out the tests for bottom sludge characterisations. Chlorophyll a was determined by the extraction method described by Pearson et al. (1987). The number of helminth eggs was estimated by using the Yanko recovery method described in USEPA (1992). Sludge stability was calculated after incubating sludge samples at 30ºC during one month after dilution with pond effluent. During this incubation the accumulated methane production was observed. Methane production was more intense during the first few days of incubation: in the first week the methane production was always more than half the total production during the test period of one month. The biodegradable sludge fraction was calculated both from the measured methane production (van Haandel and Lettinga, 1993) and the reduction of volatile suspended solids. It was observed that hydrolysis and digestion of organic material in the bottom sludge was insignificant: less than 5% of the volatile solids were digested during the incubation period of 1 month at 30ºC (see Table 1).

**Discussion**

The experimental data show that the accumulation of bottom sludge in a polishing pond for post-treatment of digested wastewater was significantly smaller than that observed in pond systems treating raw wastewater, even though no excess sludge was discharged from the UASB reactor treating the raw wastewater. This is to be expected because much of the solids and organic material of raw wastewater are converted into biogas in the preceding anaerobic reactor. It was quite clear that the relatively large sludge accumulation in the first lane of the pond (where more than half of the sludge accumulation took place) must be attributed mainly to settling of the sludge particles present in the UASB effluent. This sludge accumulation could have been reduced considerably, if regular sludge wastage from the UASB had been applied (Cavalcanti et al., 1999).

It is interesting to observe that the inorganic sludge mass in the pond influent (0.35 ¥ 244 = 85 kg) was larger than the inorganic bottom sludge mass in the first lane (77.3 ¥ 0.588 = 48 kg), whence it is concluded that not all the suspended fixed solids settled out in the first lane and/or that inorganic material (ammonia, phosphate, sulphide) was liberated from settled
organic macromolecules, when these decomposed in the bottom sludge of the first lane. The organic fraction in the first lane was very much smaller than in the other lanes, which can be attributed to the higher mineral suspended solids concentration in its influent. The UASB sludge had a volatile sludge fraction of 65%.

Even though more solids accumulated in the first lane than the subsequent ones, and the sludge mass in this lane amounted to more than half the total, the mass fraction of the bottom sludge in the lanes 2 to 5 was much higher than could be expected on the basis of presence of settleable material in the liquid phase. The effluents from the different lanes had virtually no settleable solids. It is concluded that sludge accumulation in lanes 2 to 5 could only occur because spontaneous flocculation of the suspended solids took place. These suspended solids presumably were algae, which were abundant in the liquid phase. This conclusion is corroborated by two observations: (1) when a sample of the liquid phase from lanes 2 to 5 was set aside in a beaker in the sun, after some time (1 to 2 h) a green precipitate formed at the bottom of the beaker, which showed that indeed flocculation and sedimentation did occur; and (2) chlorophyll $a$ was detected in the bottom sludges of lanes 2 to 5. The sludge in lane 1 had no detectable chlorophyll $a$ concentration, although algae were clearly present in the liquid phase.

Even under the unfavourable operational conditions of (1) a short UASB retention time and (2) no excess sludge removal from the UASB reactor, the rate of bottom sludge accumulation was very low. In Table 2, on the basis of the experimental data, an accumulation rate of 70 mg·l$^{-1}$ is estimated, and if a sludge concentration of 100 g·l$^{-1}$ is assumed (the approximate value after 1 year of operation), the volumetric bottom sludge accumulation rate is calculated at only 700 ml per m$^3$ of influent. If a yearly per capita contribution of 40 m$^3$ (equivalent to 105 l/inh/d) is adopted, the bottom sludge production is 28 l/inh·annum$^{-1}$. This is 2 to 4 times smaller than the values reported for raw wastewater treatment in anaerobic ponds (Arceivala, 1985; Gonçalves et al., 2000).

The volumetric accumulation rate depends on the liquid retention time in the pond. For example in the year the pond operated the average retention time was about 6 d so that in 1 year (360 d) about 2000 m$^3$ of digested wastewater was polished. Hence per m$^3$ of pond, the treated volume was 360/6 = 60 m$^3$ per annum, so that a volume of 0.7 70 l = 42 l of bottom sludge accumulated per m$^3$ of pond, i.e. the bottom sludge accumulated at only 4.2% per year. It is concluded that most likely there would be no need to desludge the polishing pond during its useful life span, or at least it would be possible to operate the pond for a very long time without a need for sludge removal. It must be remembered that no excess sludge was discharged from the UASB reactor producing the pond influent. Thus the data indicate that excess sludge discharge for a UASB reactor becomes optional if a polishing pond is used as a post-treatment unit. Excess sludge may be discharged if there is an advantage in producing it (for example, for sale as organic fertiliser), but if there is no such advantage this operation may be omitted and the excess UASB sludge can be discharged together with the UASB effluent in the pond. The polishing pond performance and operational stability will not be affected by the introduction of the UASB sludge. To operate ponds without bottom sludge discharge constitutes a possibility to reduce operational costs substantially.
The test of sludge stability showed that only a very small fraction (less than 5%) of the organic material was biodegradable. This is to be expected, not only because the solids from the UASB reactor have a large fraction of non-biodegradable material, generated from inert organic material in the raw wastewater, but also because the time for anaerobic digestion in the bottom sludge was very long.

The organic solids fraction averaged a value of 0.58 of the total solids. The nitrogen and phosphorus fractions of the volatile matter in the sludges from lanes 2 to 5 were approximately equal to those normally encountered in biological sludges (10% N and 2.5% P, respectively) The relatively high proportion of organic material and nutrients in the sludge, together with the excellent stability of the solids are indications that the sludge could be an organic fertilizer. However care must be taken, because the hygienic quality of the sludge is very poor. The number of helminth eggs in the bottom sludge was very high: an average of 651 eggs were found per g of dry sludge, which represents a quantity of 45 eggs per l of treated influent, about 50% of the number of helminth eggs in the digested wastewater. Even though several authors have shown that only a fraction of 0.02 to 0.10 of the eggs in bottom solids are viable (Gonçalves, 2000), the number is still very much higher than most standards. For example EPA (1992) uses a standard of 1 viable helminth egg per 4 g of sludge for use in mechanised cultures, without direct contact. It is concluded that the use of the sludge in agriculture is only feasible after thorough treatment to improve its hygienic quality.

Conclusions
1. If efficient anaerobic treatment of raw wastewater is applied, the rate of solids accumulation in the bottom sludge of polishing ponds used for post-treatment of its effluent is much lower than in anaerobic ponds treating raw wastewater, provided that no excess sludge is discharged from the pretreatment unit.
2. In tropical regions the rate of sludge accumulation in polishing ponds treating anaerobically digested wastewater is so low that desludging will probably not be necessary during the useful life of the post-treatment unit.
3. If a polishing pond is used for post-treatment of anaerobically digested wastewater, there is no need for discharge of excess sludge from the anaerobic pretreatment unit: the excess sludge can be accommodated in the polishing pond, without affecting pond performance or operational stability.
4. During post-treatment of UASB effluent in a polishing pond for a period of 1 year, the observed sludge accumulation amounted to 70 mg/l of influent, which is 2 to 4 times smaller than the value determined in anaerobic ponds treating raw wastewater.
5. The stability of the bottom sludge under the investigated conditions (average temperature of 25°C) was very good with less than 5% of the volatile solids digestible during 1 month at 30°C.
6. The hygienic quality of the bottom sludge was very poor: more than half of the helminth eggs of the UASB effluent fed to the pond persisted in the bottom sludge.
7. The organic fraction of the bottom solids as well as the nutrient concentrations were high (58% volatile matter, 0.066 gN/gVSS and 0.018 gP/gVSS), so that the sludge (after removal of the pathogens) would appear to be useful as an organic fertiliser.

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References


